REGIONAL AND FLOE-FLOE ICE DEFORMATION

Dr. James E. Overland
Pacific Marine Environmental Laboratory/NOAA
7600 Sand Point Way N.E.
Seattle, WA 98115-0070
overland@pmel.noaa.gov
Voice: (206) 526-6795; FAX: (206) 526-6485
Award No. N0001495F077

LONG-TERM PROJECT GOALS

1. Establish the scientific basis for the next generation regional sea-ice model.
2. Understand the space/time variability of wind forcing.

OBJECTIVES

1. Investigate the granular/plastic nature of sea ice, based on comparison of wind data, SAR ice motion data, and floe scale (<20 km) relative buoy motions.
2. Publish an article concerning the influence of scale on sea ice dynamics in EOS, Transactions of the AGU.

APPROACH

The idea that sea ice behaves as a plastic material on regional scales (>10 km) is over 25 years old (Karlsson, 1972), but the concept has generally not been tested. Plastic/granular motions are important to understand and model as they control when and where variations in ice thickness and concentration will occur. These variables, in turn, determine ice dynamics and thermodynamics, and air/ice fluxes. It is critical to validate ice behavior on regional scales to both initialize and validate models. Differences between model simulations and verification fields decrease with increasing height above the surface. The concept of a plastic yield curve was well established in sea-ice models of the Arctic Ice Dynamics Joint Experiment (AIDJEX) and post-AIDJEX periods. A difficulty in implementing these ideas was the lack of computer capacity to resolve the physics of plastic behavior on scales less than 100 km. Higher resolution grid lengths O(15 km) are now available for regional or Arctic basin-wide models. We are evaluating the granular/plastic hypothesis for Arctic sea ice using SAR imagery and concurrent buoy motions for winter-spring 1994 during the Sea Ice Mechanics Initiative (SIMI).

In a study accepted for publication by the *Journal of Geophysical Research*, we make use of an *in situ* buoy array and the European Earth Resources Satellite (ERS-1) Synthetic Aperture Radar (SAR), to resolve ice motions, and thus deformations, on sub-regional and regional scales during winter-spring 1994. In our study SAR-derived ice motion data from the Geophysical Processing System (AGPS) at the Alaska SAR Facility, were favorably compared with deformation obtained from an array of 11 drifting buoys equipped with Global Positioning System (GPS), deployed in a 15 $\times$ 15 km area 450 km north of Alaska as part of SIMI. A major use for

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**

4. TITLE AND SUBTITLE **Regional and Floe-floe Ice Deformation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Oceanic and Atmospheric Administration (NOAA),Pacific Marine Environmental Laboratory,7600 Sand Point Way N.E.,Seattle,WA,98115-0070**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

SAR in our study was to verify sea-ice dynamics assumptions through case studies of regional deformation events using an exact 3-day repeat coverage of a mosaic area, approximately 80 x 500 km. We also wished to understand whether this information could be scaled up for inclusion in Arctic basin models. In particular, we investigated whether sea ice under compression yields primarily in shear. Because deformation in the wind field is often not large enough to cause significant deformation in the ice pack at scales less than 200 km, regional-scale ice deformation 0(10–200 km) should primarily be a function of internal ice dynamics, coastal geometry, and large-scale wind direction and magnitude.

ACCOMPLISHMENTS

As an example, we describe selected results from winter 1994. Two major onshore wind events, one in February and the other in March 1994, demonstrate the underlying plastic material hypothesis for sea ice. Figure 1 shows 3-day SAR relative displacement vectors at a 10 km spacing for a region north of the North Slope of Alaska for 10-12 February (days 41-44) with the mean motion of the scene removed. The location of the buoy array is indicated by the circle centered at 75.0°N, 156°W. The motion vectors are co-registered with a Thermal Infrared (TIR) AVHRR image from 10 February. The AVHRR image features represent conditions at the start of the 3-day observation period and correspond to the origin points of the vectors plotted from the SAR data. We visually inspect the motion fields for discontinuities. We look at the raw displacement vectors, vectors with the displacement of the buoy array removed from the raw displacements, and with the mean motion of the scene removed. All three are necessary to infer motion discontinuities denoted by the heavy lines drawn on the SAR relative motion plot. The ice was moving south-southeast under northwest winds. A fast ice zone is along the southern portion of Figure 1. The differential motion near the buoy array occurs along a northwest-southeast trending shear boundary or slipline, which was also observed in the buoy motions (Figure 2), and continues southward where it intersects another shear line. Figure 2 shows the 3-day motions within the buoy array with the central thick arrow giving the translation of the array, i.e., toward the southeast, and the thinner arrows showing relative buoy motions with slipline behavior. For the following three days (days 44-47) the ice continued to move southward but the ice floes in the buoy array had advected out of the region of the slipline. There are indications of two discontinuities (dotted lines) in the middle of the SAR image running in an east-northeast direction nearly perpendicular to the wind direction. Overall, the relative displacement vectors show the ice moving in different relative directions within zones defined by velocity changes suggesting uniform motion within aggregate regions.

As the ice converges under northerly winds, sliplines occur at an acute angle to the wind forcing and to each other. This orientation is a prediction of the critical state hypothesis for a plastic material with shear stress proportional to compressive stress, i.e. $\sigma_{II} \propto \sigma_I$. However, observed angles between sliplines were smaller than those predicted by theory, and the regular diamond pattern of autumn leads seen by Marko and Thomson (1977) were not observed during February and March. As the implied normal ice stress increases toward the coast because of increased fetch, there is a discontinuity in the ice motion normal to the wind direction where one

infers failure due to compression when the ice strength P* is reached, i.e. $\sigma_I \sim P^*$. Ice floes tend to move in aggregate blocks O(20–150 km).

The sliplines we drew on the SAR data separated the ice into aggregates whose size and behavior are consistent with granular plastic behavior. The relative buoy displacements also indicate little opening in the ice, which is not consistent with a normal flow rule. However, it may be possible to have characteristic Coulomb slipline directions and a normal flow rule without large openings in the ice, because the ice deforms into ridges along the shearlines, i.e., out of the plane, with minor opening within the aggregates.

SCIENTIFIC/TECHNICAL RESULTS

We have had success in directly validating that sea ice behaves as a hardening, granular, plastic material. Our study was based on analyses of AVHRR imagery, 11 drifting buoys and ERS-1 SAR motion vectors in an 80 x 500 km swath north of Alaska. At moderate atmospheric forcing, i.e., windstress multiplied by fetch, the ice appears to fail along sliplines which occur at an acute angle to each other and to the direction of the wind forcing, characteristic of a plastic material at critical state. With longer fetch, the ice appears to fail in compression, perpendicular to the wind direction. Beaufort sea ice tends to move in 20-150 km rigid plates separated by linear deformation zones. Understanding such processes is necessary for correctly modeling the air/ice/ocean system and inferring thermodynamic coupling.

REFERENCES:

Karlsson, T., A viscoelastic-plastic material model for drifting sea ice, in SEA-ICE: Proceedings of an International Conference, National Research Council, Reykjavik, Iceland, R.r. 1972–4, pp. 188–195, 1972.

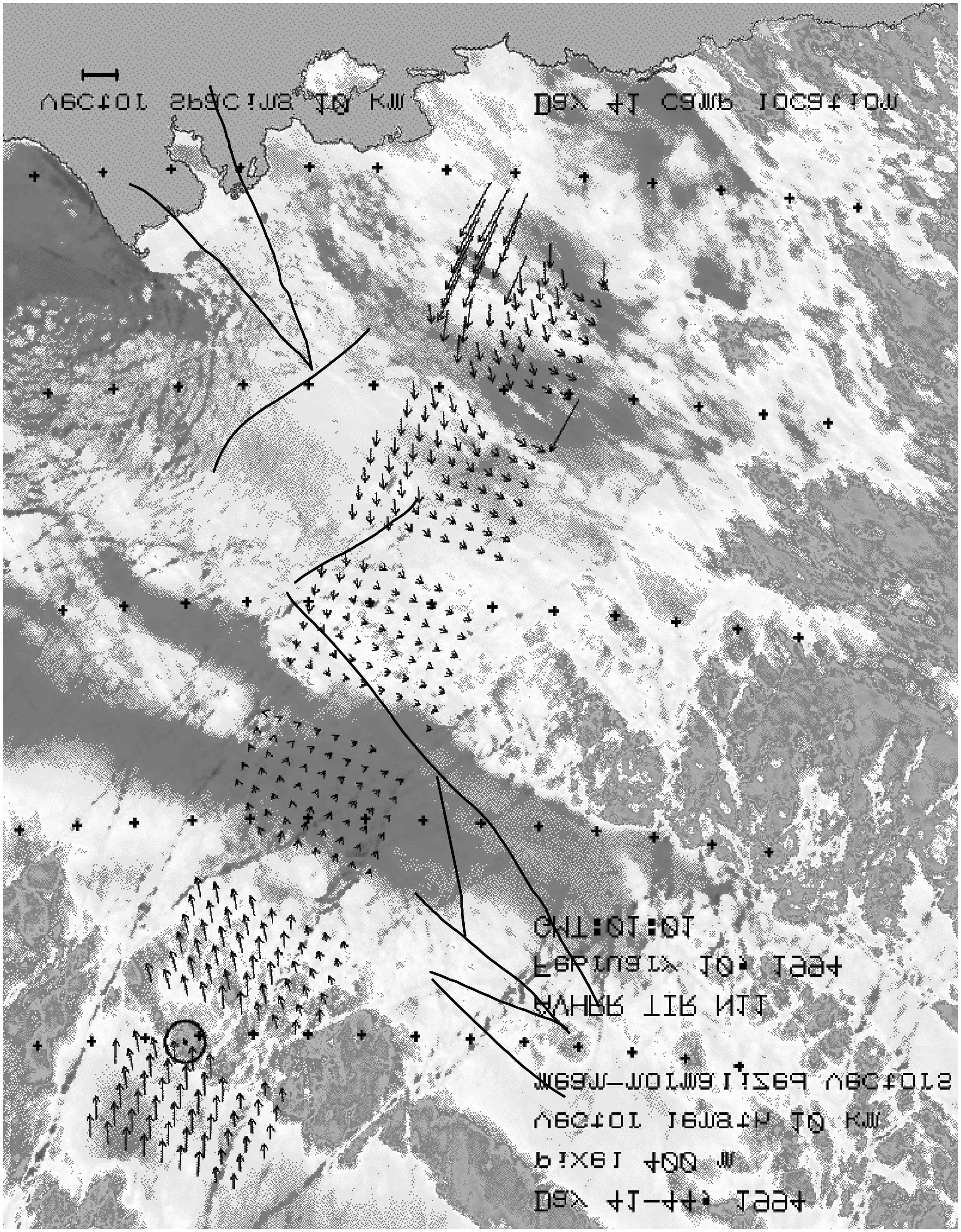
Marco, J., and R. Thomson, Rectilinear leads and internal motions in the ice pack of the western Arctic Ocean, *J. Geophys. Res., 82*, 979–987, 1977.

PUBLICATIONS

Overland, J.E., and W. F. Weeks (1996): Studying Arctic sea ice at two scales provides more accurate picture. *EOS, Trans. AGU, 77*(50), 501, 505-506.

Overland, J.E., J.M. Adams, and N.A. Bond (1997): Regional variation of winter temperatures in the Arctic. *Journal of Climate*, 10(5), 821-837.

Overland, J.E., L. McNutt, S. Salo, J. Groves, and S. Li (1998): Arctic sea ice as a granular material. *J. Geophys. Res*. (In press).



Day 41-44, 1994
pixel 400 m
vector length 10 km
mean-normalized vectors
AVHRR TIR N11
February 10, 1994
GMT:01:01
Day 41 camp location
vector spacing 10 km

2. Relative displacements of buoy array show slipline behavior for days 41-44, 1994.